ESTIMATING SOIL HEAT FLUX FOR ALFALFA AND CLIPPED TALL FESCUE GRASS

J. O. Payero, C. M. U. Neale, J. L. Wright

ABSTRACT. *Soil heat flux (G) is an important component of evapotranspiration (ET) modeling, especially for estimating ET values for hourly or shorter periods. In this study, meteorological and agronomic measurements were made at Kimberly, Idaho, with the purpose of establishing empirical relationships to estimate G for alfalfa and clipped tall fescue grass. For both plant surfaces, good linear correlation was found for most days between the averages of the 20-min net radiation (R_n) and G values for a given day. However, when the soil surface was wet, after rain or irrigation, the relationship was subject to hysteresis problems. The linear relationship between G and R_n for alfalfa also changed with plant canopy height (h), and an equation was derived to estimate G from R_n and h (r^2 = 0.88). This equation fitted measured G data much better than two other commonly used models (Allen et al., 1996; Clothier et al., 1986). For tall fescue grass, h did not affect the relationship between R_n and G, as the grass was clipped weekly resulting in a narrow range of h (0.09 to 0.19 m). A linear equation to estimate G as a function of R_n (r^2 = 0.91) was derived for clipped tall fescue grass, which was found to fit measured data equally well as the model proposed by Allen et al. (1998), but that uses a single equation for both daytime and nighttime instead of two separate equations.*

Keywords. *Tall fescue grass, Alfalfa, Soil heat flux, Energy balance, Evapotranspiration (ET).*

Soil heat flux (G) represents the amount of radiant energy absorbed or released at the soil surface during a given time period. It is an important component of the energy balance of crop canopies and it is commonly included in models to calculate soil evaporation and crop evapotranspiration (ET) (Allen et al., 1998; EWRI, 2001). Although G is sometimes disregarded in daily ET models, its contribution to ET could be significant (Kumar and Rao, 1984). When ET is calculated more frequently than daily, the contribution of G is even more significant, especially for conditions of sparse vegetation (Payero et al., 2003). Evett et al. (1994) found that omitting the G and the reflected shortwave radiation terms from a model developed to estimate soil evaporation reduced model accuracy by as much as 9.2%. Similarly, Jiang and Islam (2001), when trying to estimate surface evaporation over large heterogeneous areas using remote sensing, realized that the uncertainty in the estimation was due to the inaccuracy in estimating net radiation (R_n) and G. Arshad and Azooz (1996) reported measured hourly G values from a barley crop, which fluctuated between approximately –30 W m^{-2} during nighttime and 75 W m^{-2} at midday. For hourly ET calculations, these midday G values could represent approximately 10% to 20% of ET.

Soil heat flux can be affected by a series of factors. For instance, Beringer et al. (2001) found that mosses covering soils in high northern latitudes decreased G by 57% in July. Sharratt and Flerchinger (1995) found that G was affected by barley straw color covering soils. Arshad and Azooz (1996) found differences in measured G in soils under conventional tillage, no-tillage, and modified no-tillage. Gupta et al. (1984) found that hourly G was higher for bare soil than for residue-covered soil for the same tillage condition. Malek (1993) found that in addition to solar and net radiations, cloudiness, wind speed and direction also affected 20-min G averages measured in the middle of an alfalfa field. Payero et al. (2003) reported differences in the near-noon G/R_n ratios as a function of plant canopy heights for grass and alfalfa. Idso et al. (1975) and Evett et al. (1994) reported differences in measured G values due to differences in soil moisture. Evett et al. (1994) found that the magnitude of G was much lower for a dry soil compared with a drying soil, especially in the first few days after irrigation. They attributed the difference to the greater thermal conductance of the wet soil. Idso et al. (1975), on the other hand, found that for bare soil conditions, the slopes of the G versus R_n relationships essentially doubled in going from wet to dry soil, which implies that for a given R_n, the G value would be higher for a dry soil compared to a wet soil. The effects of spatial variability on G measurements can be significant and have been discussed by Fritton et al. (1976) and by Stannard et al. (1994).

Soil heat flux can be measured using soil heat flux plates. These measurements, however, need to be corrected for heat stored above the soil heat flux plates. The correction is usually estimated using measurements of soil temperature and moisture close to the soil surface (Hanks and Ashcroft, 1980). Soil heat flux can also be derived from other

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measurements, such as soil temperature profile close to the surface. For instance, Horton and Wierenga (1983) proposed a method based on a Fourier series to estimate hourly G values by measuring soil moisture and soil temperature at two or three depths near the soil surface. Gupta et al. (1984) used a similar Fourier series model to estimate hourly G values from daily maximum and minimum air temperatures, thermal diffusivity, and volumetric heat capacity of the soil. Other methods to estimate G from soil temperature measurements have been presented by Massman (1993), Hares et al. (1985), Braud et al. (1995), and Wang and Bras (1999).Since the variables needed to apply these methods, however, are not routinely measured by standard weather stations, procedures need to be developed to obtain G estimates from other easily available variables.For example, R_n, which can be calculated from standard weather station data (Allen et al., 1998), is often used to estimate G (Idso et al., 1975; Sene, 1994; Allen et al., 1996). Soil heat flux has been estimated for different surfaces using several methods, some of which consider G to be a simple fraction of R_n. Malek et al. (1997), for example, developed relationships to estimate surface and 8-cm soil heat fluxes for a desert valley. Sene (1994) proposed the following equation for a sparse vine crop:

$$G = 0.26R_n - 21 \tag{1}$$

where R_n and G are in W m^{-2}.

This equation assumes a constant G/R_n ratio, independently of plant canopy height. Moran et al. (1989, 1994) and Reicosky et al. (1994) calculated G from R_n and the remotely sensed Normalized Difference Vegetation Index (NDVI) as:

$$G = R_n(0.583e^{-2.13NDVI}) \tag{2}$$

Equation 2, unlike equation 1, considers a decreasing G/R_n ratio with increasing plant canopy height. Support for this concept can also be found in data obtained by Gutierrez and Meinzer (1994), and Payero et al. (2003). Choudhury et al. (1987) estimated G for wheat as a function of R_n and leaf area index (LAI) as:

$$G = 0.4(e^{-0.5LAI})R_n \tag{3}$$

This equation, like equation 2, considers decreasing G/R_n with increasing plant canopy cover. A similar model to estimate G from R_n and LAI for corn and potato was proposed by Kjelgaard et al. (1996). Clothier et al. (1986) estimated G for alfalfa as a function of R_n and plant canopy height (h). They found that at midday, $G = 0.099R_n$ for $h \geq 0.45$ m, and for $h < 0.45$ m the midday G could be determined using the following equation ($r^2 = 0.77$):

$$G = (0.283 - 0.4096h)R_n \tag{4}$$

Since it was intended for remote sensing applications, this equation was derived using only data obtained at midday. It, therefore, cannot be used to calculate G at other times of the day. Camuffo and Bernardi (1982) proposed the following model to calculate G as a function of time:

$$G(t) = a_1 R_n(t) + a_2\left(\frac{\partial}{\partial t}\right)R_n(t) + a_3 \tag{5}$$

where t is time (h), and a_1, a_2, and a_3 are coefficients, which should be obtained empirically for each particular crop and location. They, however, did not provide values for these coefficients. They also did not consider the variation of the G/R_n ratio with changing canopy cover. Allen et al. (1998) proposed estimating G for hourly or shorter periods for a short-growing crop like grass (h = 0.12 m) using a fixed G/R_n ratio of 0.1 during daytime and 0.5 during nighttime. Ventura et al. (1999), however, proposed using a smaller G/R_n ratio of 0.03 to 0.05 to estimate daytime G values for a 0.10- to 0.15-m tall grass. Allen et al. (1996) and EWRI (2001) proposed using $G/R_n = 0.04$ for alfalfa (h = 0.5 m) for daytime and $G/R_n = 0.2$ for nighttime. These models, however, do not deal with the problem of changing plant canopy heights.

Procedures are needed to estimate G during the entire daily cycle and covering the entire growing period of specific crops. This is especially needed for clipped grass and alfalfa, since they are commonly used as reference surfaces for calculating reference evapotranspiration (Allen et al., 1998; EWRI, 2001). The purpose of this study was to document how G changes during the diurnal cycle and during a growing season for alfalfa and clipped tall fescue grass. An additional objective was to develop empirical equations to estimate G during the entire daily cycle and throughout different growth stages.

Methods

Data for this study were collected from two adjacent, similar sized (2.6-2.7 ha), alfalfa and clipped tall fescue grass fields at Kimberly, Idaho (Latitude = 42.4° N, Longitude = 114° W). The nearly flat, furrow-irrigated fields have a Portneuf silt loam soil (Wright, 1991). Measurements for this study were made using a model 023A Bowen ratio system (Campbell Scientific, Inc., Logan, Utah), previously described by Tanner et al. (1987), which was interchanged between the two fields. The system was installed in the alfalfa field from day of the year (DOY) 182 to 212 (1 July to 31 July), and from DOY 231 to 267 (19 August to 24 September) of 1991, which included two growing cycles. Measurements in the tall fescue grass field were made from DOY 213 to 231 (31 July to 19 August). The tall fescue grass was mowed every week to a height of approximately 0.09 m using a lawn mower.

Net radiation was measured using a REBS-Q5 net radiometer (Radiation and Energy Balance Systems, Inc., Seattle, Wash.), which was cross-calibrated with a Swissteco (Oberriet, Switzerland) net radiometer as described by Payero et al. (2003). The sign convention for the direction of fluxes in this study followed that used by Tanner (1960), according to which R_n and G are positive when the flux is downward. Soil heat flux was calculated from measurements obtained using two HFT3 soil heat flux plates and four copper-constantan soil thermocouples (Campbell Scientific, Inc., Logan, Utah) (Malek, 1993). Each soil heat flux plate was placed at a depth of 0.08 m below the soil surface. Two soil thermocouples were installed near each soil heat flux plate at depths of 0.02 and 0.06 m below the soil surface. Sensor outputs were sampled every 10 s, and averages were stored every 20 min using a 21X Micrologger (Campbell Scientific, Inc., Logan, Utah). Soil heat flux was calculated using the following procedure (Hanks and Ashcroft, 1980):

$$G = SHF + S \tag{6}$$

$$S = (T_i - T_{i-1}) \times D \times C_s/t \tag{7}$$

$$C_s = BD \times (C_{sd} + W \times C_w) \quad (8)$$

where SHF = flux measured by the soil heat flux plates (W m^{-2}), S = change in heat stored above the soil heat flux plates (W m^{-2}), T_i = soil temperature during current time interval (°C), T_{i-1} = soil temperature during previous time interval (°C), D = depth to soil heat flux plates (m), C_s = heat capacity of soil (J m^{-3} °C^{-1}), t = time interval (s), BD = soil bulk density (Kg m^{-3}), C_{sd} = specific heat of mineral soil (J Kg^{-1} °C^{-1}), W = soil water content on a mass basis (Kg Kg^{-1}), and C_w = specific heat of water (J Kg^{-1} °C^{-1}). A reasonable value for C_{sd} is usually taken as 840 J Kg^{-1} °C^{-1} and that for C_w, 4190 J Kg^{-1} °C^{-1}. Soil moisture was obtained from gravimetric samples taken about every three days from a depth of 0 to 0.1 m. Plant canopy height was measured approximately every three days. The average of 20 measurements, without straightening the plants, was taken as the plant canopy height for a given day. Leaf Area Index (LAI) was also measured weekly from samples taken from both fields, using a LI-3050A optical area meter (LI-COR, Inc., Lincoln, Nebr.). Values of soil moisture, h, and LAI between measurements were estimated by linear interpolation.

Results and Discussion

Crop Development

The measured h values (fig. 1) indicate that the first alfalfa growing cycle experienced a normal growing pattern, while the second cycle suffered from lodging problems. Lodging was due to a combination of heavy rain and gusty winds that occurred when plants reached a height of approximately 0.55 m. The alfalfa plant canopy reached a height of 0.75 m during the first growing cycle and only 0.58 m during the second cycle. Figure 1 also shows that the tall fescue grass field was mowed four times during the study period. Plant canopy height for tall fescue grass, therefore, only fluctuated between 0.09 and 0.19 m.

Results of regression analysis show that a good linear correlation between h and LAI existed for alfalfa (table 1). For tall fescue grass, on the other hand, no significant linear relationship was found between h and LAI, which could be due to the small range of plant heights included in the analysis.

Soil Moisture

Daily soil moisture values used to calculate G for both fields are shown in figure 2. Sharp increases in soil moisture indicate times when the soil was wetted by either rain or irrigation. The alfalfa field was wetted five times by heavy rain or irrigation and was well watered at the beginning of each growing cycle. The tall fescue grass field, on the other hand, was wetted eight times during the same period, since its shallower roots required more frequent irrigation for adequate growth.

Diurnal Pattern of G and R_n

Diurnal G and R_n patterns for 0.5-m alfalfa (DOY 201) and 0.12-m tall fescue grass (DOY 220), which are representatives of typical R_n and G diurnal patterns are shown in figure 3. These plant canopy heights were selected since these are the heights taken as reference heights for the standardized ET equation recently proposed by EWRI (2001). Results show that G follows changes in $R_{n.}$ For instance, when R_n for alfalfa suddenly decreased in the afternoon of DOY 201, due to cloudy conditions, G also decreased (fig. 3). A smooth G pattern, on the other hand, was observed for tall fescue grass during the clear-sky conditions of DOY 220. Figure 3 also points out that when short time steps are considered (such as hourly), G can be a significant

Table 1. Linear regression parameters for the relationship between plant canopy height (m) and leaf area index for alfalfa and tall fescue grass.

Regression Parameter	Alfalfa	Tall Fescue Grass
Intercept	-0.72	3.5
Slope	9.28	-2.78
P value (intercept)	0.07	0.013
P value (Slope)	4.4×10^{-8}	0.614
r^2	0.92	0.04
n[a]	14	8

[a] n = number of data pairs.

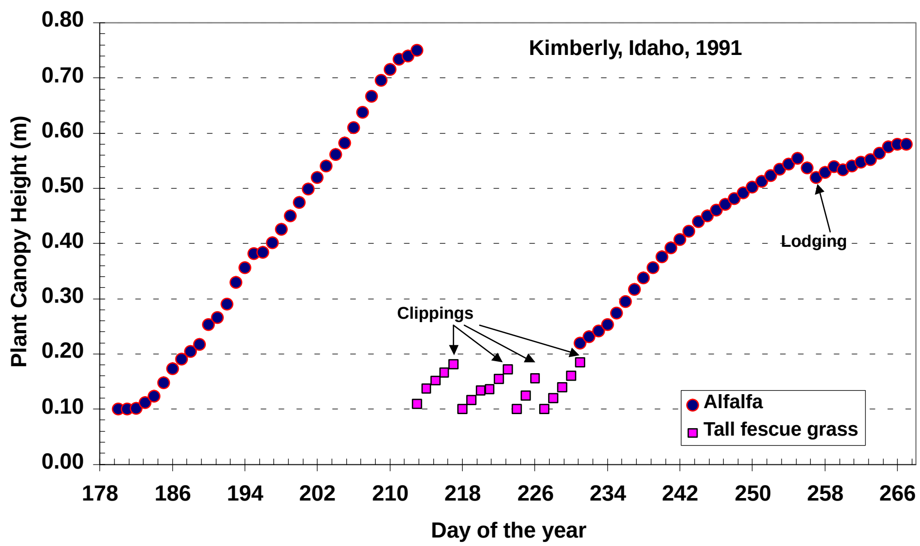

Figure 1. Plant canopy height for alfalfa and tall fescue grass during the 1991 study at Kimberly.

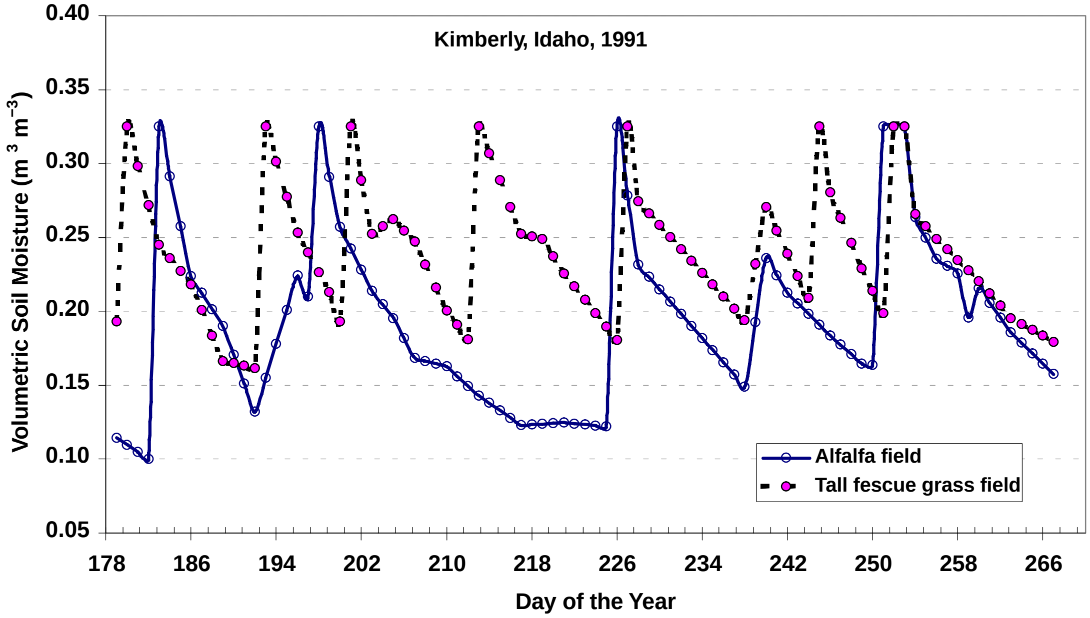

Figure 2. Soil moisture for the alfalfa and tall fescue grass fields during the 1991 study at Kimberly.

component of the energy balance of a crop canopy. For instance, during midday of DOY 220 the magnitudes of G and R_n for tall fescue grass were approximately 100 and 600 W m^{-2}, respectively. Similar values were also observed during midday for alfalfa on DOY 201. This means that G represented approximately 17% of R_n during the midday period. Disregarding G in hourly ET calculations, therefore, would result in significant error.

Day-to-Day Pattern of G and R_n

The values of measured R_n and G for alfalfa during the first growing cycle are shown in figure 4. A similar pattern was observed during the second growing cycle. The range of the G values during a given day decreased with increasing plant canopy height. At the beginning of the growing cycle, when the crop was short, G values during the daily cycle ranged from approximately –100 to 230 W m^{-2}. This range steadily decreased with increasing plant canopy height, to the point where at the end of the growing cycle, G values ranged only from approximately -50 to 70 W m^{-2}. Since the daily range of R_n values during the same period was relatively constant (fig. 4), ranging from approximately -100 to 600 W m^{-2}, the decline in the range of G values is attributed to increased plant canopy cover. The magnitude of the G values shown in figure 4 further highlights the importance of including G to calculate ET for hourly or shorter periods, especially at the beginning of the alfalfa growing cycle. As an example, a peak G value at the beginning of the growing cycle of approximately 200 W m^{-2}, measured close to noon in this study, represented approximately 33% of R_n. In this case, assuming G = 0 would represent a considerable error in the calculated ET values during the near-noon period. The average daily G/R_n ratio for alfalfa linearly decreased with increasing plant canopy height as follows ($r^2 = 0.80$):

$$\text{Daily } G/R_n = -0.49\ h + 0.53 \tag{9}$$

The P values for the slope and intercept of this relationship were 2.0×10^{-9} and 1.2×10^{-16}, respectively, which were both statistically significant.

For tall fescue grass, the diurnal range of the measured G values during DOY 213 to 231was between approximately –50 and 100 W m^{-2}. No effect of plant canopy height on the

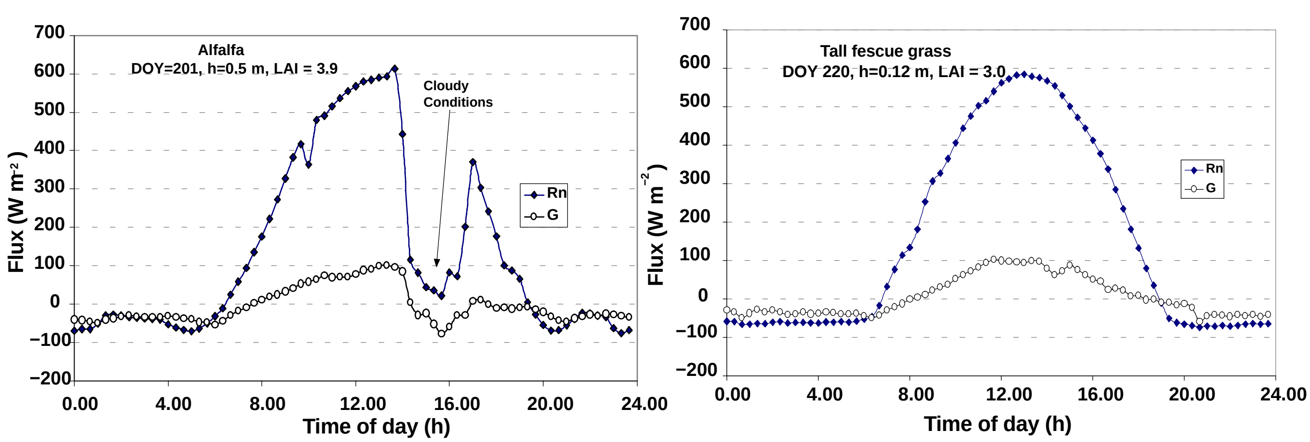

Figure 3. Diurnal pattern of net radiation (R_n) and soil heat flux (G) for a 0.5−m alfalfa and a 0.12−m tall fescue grass during 1991. Each point represents a 20−min average.

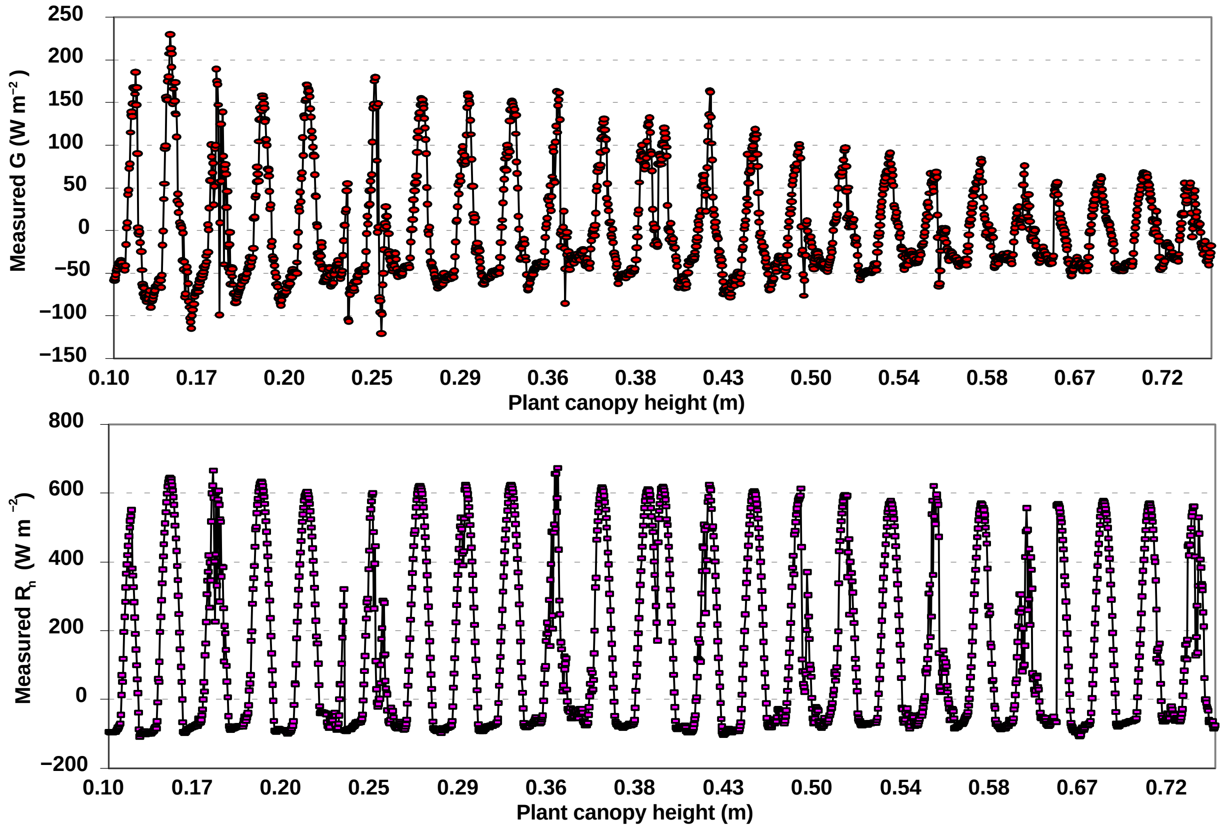

Figure 4. Measured net radiation (R_n) and soil heat flux (G) for alfalfa during the 1991 study at Kimberly. Each point represents a 20−min average obtained during DOY 182 to 210.

range of G values, however, was observed for tall fescue grass over the range of plant canopy heights included in this study.

Relationship Between G and R_n

Alfalfa

On a daily basis, the 20-min G values for alfalfa were usually linearly related to R_n, but occasionally the relationship suffered from hysteresis problems (fig. 5). For example, for DOY 184 different G values for a given R_n occurred during the midnight to noon hours compared to the noon to midnight hours, since the diurnal G and R_n waves did not reach their peak values at the same time. Hysteresis in the diurnal relationship between G and R_n has previously been reported by Camuffo and Bernardi (1982), Novak (1993), and Domingo et al. (2000).

To evaluate the extent and cause of the hysteresis problem, a linear regression analysis between the 20-min R_n and G values was conducted for each day during the two alfalfa growing cycles. Based on the observed nature of the relationship between R_n and G for a particular day, the r^2 values resulting from this analysis could be interpreted as indicative of the degree of hysteresis, the lower the r^2, the more pronounced the hysteresis. Figure 6 indicates that lower r^2 values resulted when the soil surface was wet, during days following rain or irrigation, which accounted for most of the observed hysteresis problems. Hysteresis should be expected on the day when the soil is wetted and as the soil surface dries after initial wetting since the G values for a given R_n are different for wet and dry soil conditions (Idso et al. 1975; Evett et al. 1994).

In addition to the hysteresis caused by soil surface wetness, some hysteresis was also observed at the beginning of the first growing cycle. This problem, however, decreased later in the season as the crop grew, suggesting that the hysteresis problem was related to canopy cover conditions (fig. 5). This problem, however, was not observed at the beginning of the second growing cycle, except for days following rain or irrigation. One possible explanation for the difference in hysteresis observed at the beginning of the two growing cycles could be the soil moisture conditions at the time the sensors were installed. During the first growing cycle, the soil heat flux plates and soil thermocouples were installed in a dry soil surface, with irrigation applied a couple of days after the sensors were installed. In the second growing cycle, on the other hand, the sensors were installed in a moist soil, since the field had been irrigated a few days prior to installation. This difference might have affected the contact between the soil and the sensors, which might have affected sensor outputs at the beginning of the two growing cycles.

A multiple regression analysis was performed to derive an equation to estimate G from R_n and h. Because of the observed effect of surface wetness on hyteresis, days following rain or irrigation were excluded from the analysis. Also, because of the lodging problem during the second growing cycle, data collected after the lodging problem occurred were excluded. The analysis resulted in the following equation:

$$G = 0.372R_n + 42.78h - 0.377h \times R_n - 47.9 \qquad (10)$$

Statistics presented in table 2 show that all terms included in this equation were statistically significant (P value < 0.01).

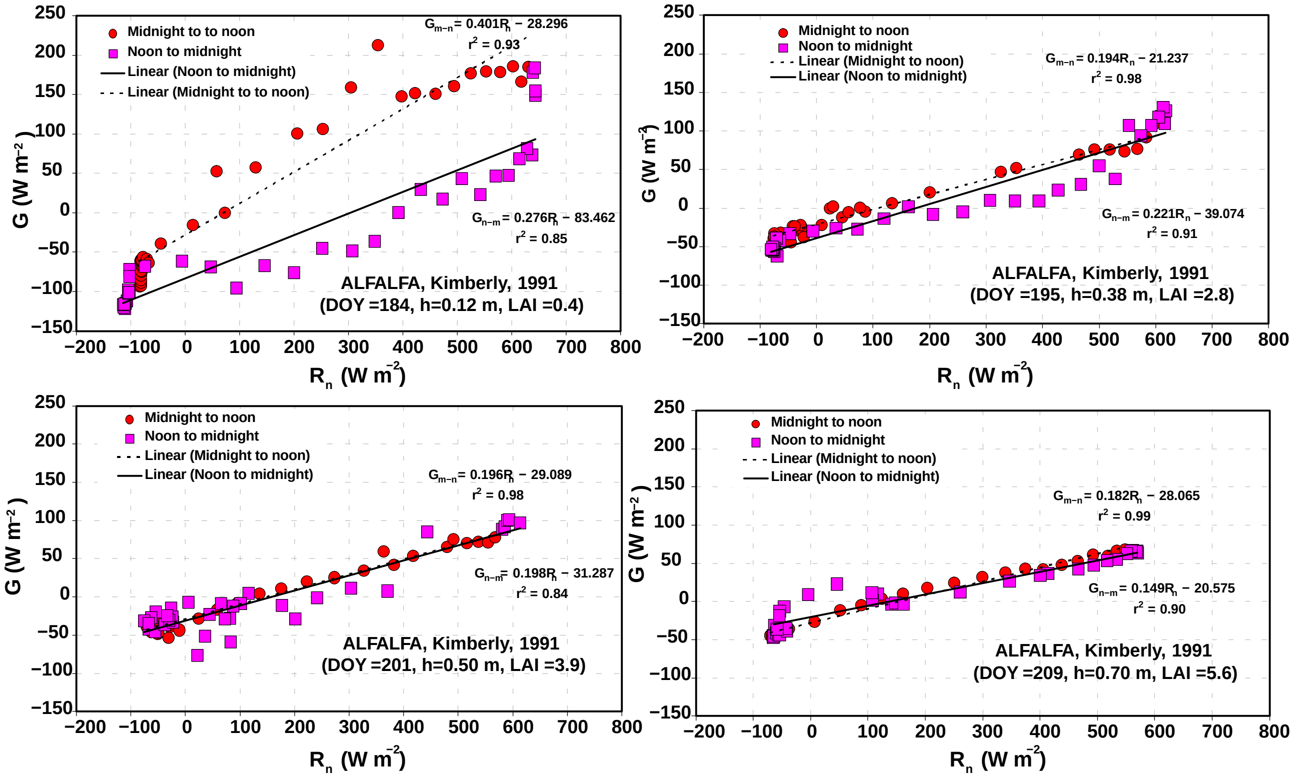

Figure 5. Relationships between net radiation (R_n) and soil heat flux (G) for different plant canopy heights (h) for alfalfa. Each point represents a 20−min average. The relationships between R_n and G were statistically significant ($p < 0.01$) for all four days. G_{m-n} is G from midnight to noon, and G_{n-m} is G from noon to midnight.

Excluding the h × R_n term from the regression model resulted in a reduction in r^2 from 0.88 to 0.81.

Tall Fescue Grass

For tall fescue grass, the 20-min G and R_n averages for a given day were well correlated (fig. 7). In fact, the regression analysis between R_n and G for each day always resulted in r^2 values greater than 0.90, except for days when the soil surface was wet. Linear regression analysis using the 20-min G and R_n averages for the entire study period (DOY 213-230), excluding days when the soil surface was wet, which included 1003 data pairs, resulted in the following equation ($r^2 = 0.91$, P value < 0.01):

$$G = 0.167R_n - 25.31 \qquad (11)$$

Including h in a multiple regression analysis, however, showed that the effect of h on G was not statistically significant (P value = 0.447), and was therefore excluded from the regression model.

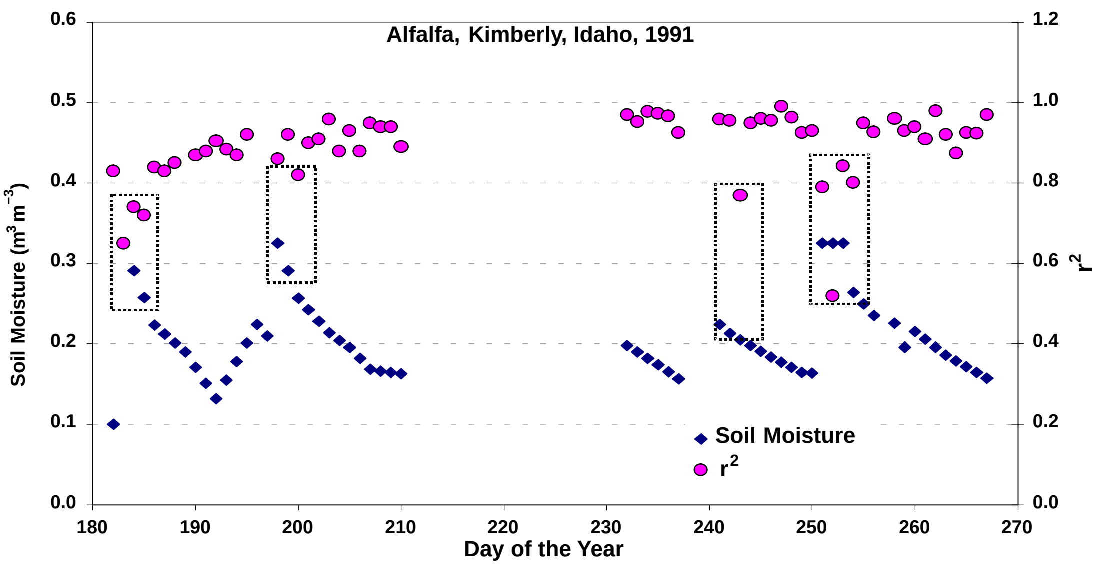

Figure 6. Effect of soil moisture conditions on the resulting r^2 of the relationship between R_n and G for alfalfa, including two growing cycles. The rectangular boxes indicate days when the soil had recently been wetted and consequently the relationship between R_n and G resulted in relatively low r^2.

Table 2. Statistics for the multiple regression analysis to estimate soil heat flux (G) from net radiation (R_n), and plant canopy height (h) for alfalfa at Kimberly.[a]

n	r^2	SEE ($W\ m^{-2}$)	P values: Intercept	$R_n \times h$	h	R_n
2856	0.88	19.2	0	5.8×10^{-284}	1.7×10^{-65}	0

[a] Analysis included 20−min R_n and G averages collected from DOY 182−213 and from DOY 231 to 254 (n is the number of data pairs and SEE is Standard Error of Estimate).

Comparison with Other Models

The models derived in this study to estimate G for alfalfa and tall fescue grass (eqs.10 and 11) were compared with other commonly used models found in the literature. For alfalfa, the models proposed by Allen et al. (1996), and that proposed by Clothier et al. (1986) were selected for comparison. Allen et al. (1996) proposed using $G/R_n = 0.04$ for alfalfa (h = 0.5 m) for daytime and $G/R_n = 0.2$ for nighttime. This model was selected for comparison because it is the one most commonly used by ET researchers. The model proposed by Clothier et al. (1986), on the other hand, was selected because it includes h as an independent variable (see eq. 4). For grass, the model by Allen et al. (1998), which proposed using $G/R_n = 0.1$ during daytime and $G/R_n = 0.5$ during nighttime (h = 0.12 m), was selected for comparison mainly because it is the model most commonly used by ET researchers.

Comparison in figure 8 shows that for alfalfa, equation 10 fitted the measured G values a lot better than both the Allen et al. (1996) and Clothier et al. (1986) models. The model by Allen et al.(1996) did not respond to changes in canopy height, which was expected since it was designed for a constant alfalfa canopy height of 0.5 m. It, however, tended to underestimate G during the entire growing cycle, even when h = 0.5 m (DOY 201). The model by Clothier et al. (1986), on the other hand, responded to changes in plant canopy height, but also tended to underestimate G. Both, the Allen et al. (1996) and Clothier et al. (1986) models estimated minimum G values during nighttime of approximately -25 W m^{-2}, while the measured values ranged from approximately -90 W m^{-2} at the beginning of the growing cycle to approximately -40 W m^{-2} at the end of the growing cycle. The calculated Root Mean Square Error (RMSE) values for the different models (table 3) show that equation 10 resulted in the lowest RMSE and the model of Allen et al. (1996) resulted in the highest. The RMSE of the Allen et al. (1996) model was twice as much as that of equation 10, while that of the Clothier et al. (1986) model was 1.5 times as high.

For grass, on the other hand, both equation 11 and the model by Allen et al. (1998) fitted the measured G values quite well (fig. 9). Equation 11, however, tended to fit the measured data a little better during the peak G periods, which may have resulted in the little lower RMSE values for equation 11 shown in table 3. The difference of 3.2 W m^{-2} in the RMSE values between the two models, however, is insignificant compared with the errors commonly incurred when measuring G and R_n. It, therefore, can be concluded that the two models are equivalent. Equation 11, however, has the advantage that one equation works for the entire daily cycle, while the model by Allen et al. (1998) requires separate equations for daytime and nighttime.

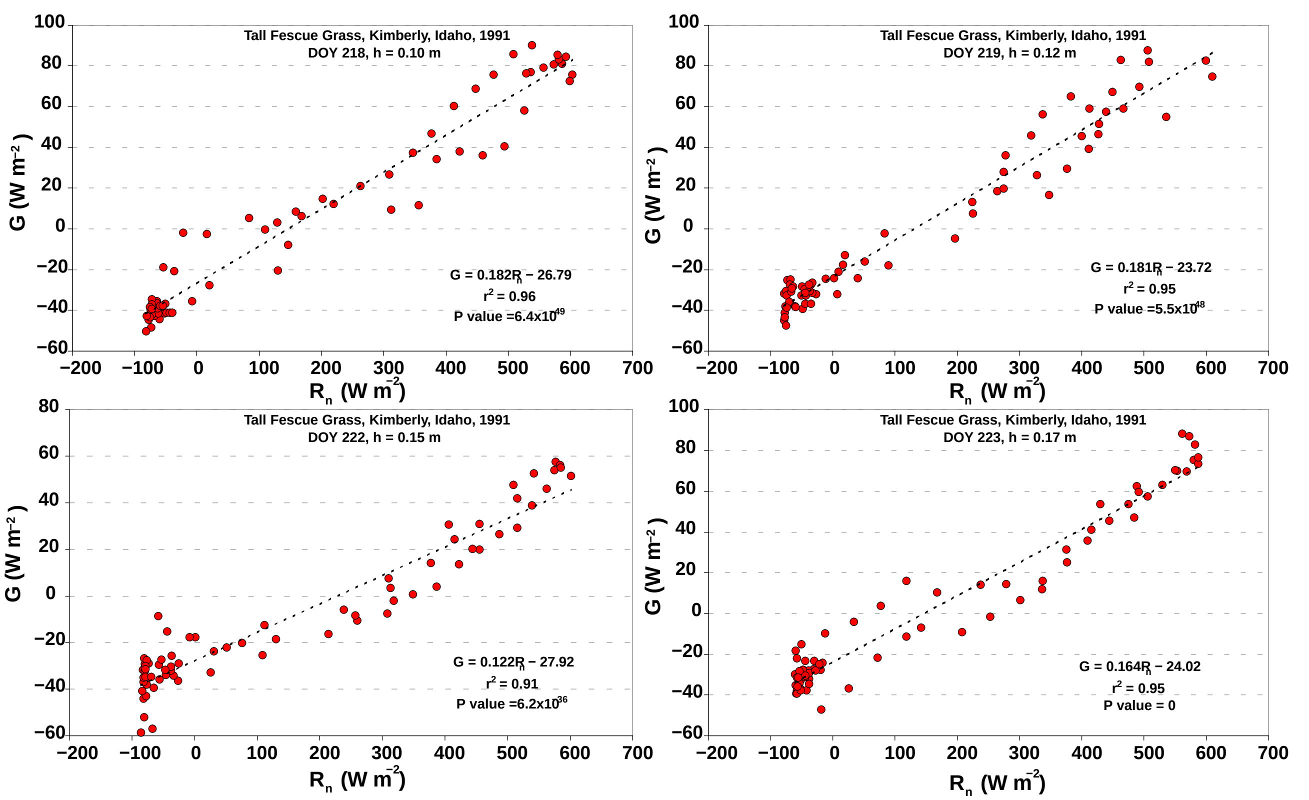

Figure 7. Relationships between net radiation (R_n) and soil heat flux (G) for four different days, which included different plant canopy heights (h) for tall fescue grass at Kimberly. Each point represents a 20−min average.

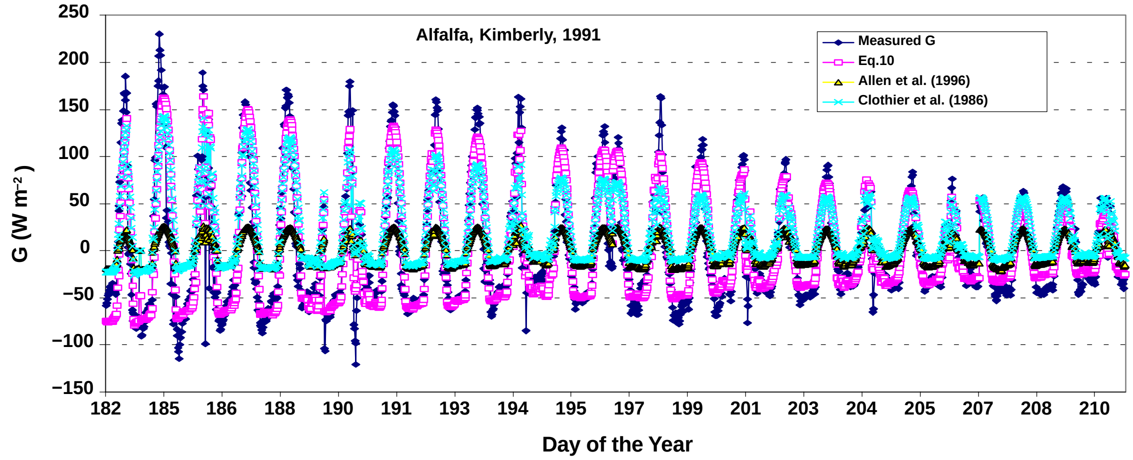

Figure 8. Comparison of measured 20−min soil heat flux (G) averages with those estimated using three different models for alfalfa at Kimberly (1991).

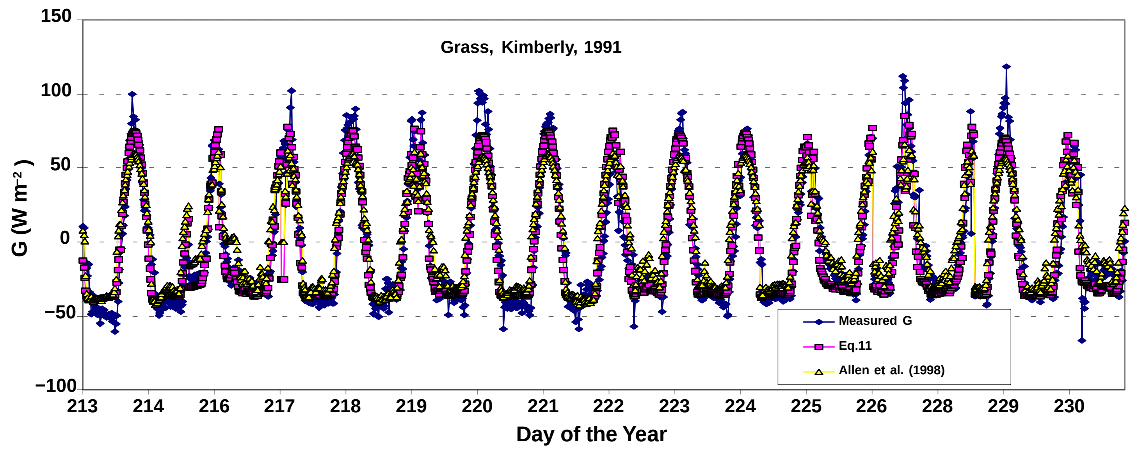

Figure 9. Comparison of measured 20−min soil heat flux (G) averages with those estimated using two different models for tall fescue grass at Kimberly (1991).

Table 3. Root Mean Square Error (RMSE) between measured soil heat flux (G) 20−min averages and those estimated with different models for alfalfa and tall fescue grass at Kimberly (1991).[a]

Model	RMSE for Alfalfa ($W\ m^{-2}$)	RMSE for Tall Fescue Grass ($W\ m^{-2}$)
Equation 10	24.4	−
Allen et al. (1996)	48.7	−
Clothier et al. (1986)	37.4	−
Equation 11	−	13.9
Allen et al. (1998)	−	17.1

[a] The number of 20−min G averages used in the analyses was 1755 for alfalfa and 1142 for grass.

Conclusion

In this study, diurnal and day-to-day patterns of G and R_n for alfalfa and tall fescue grass at Kimberly were documented. Also, empirical relationships were derived to estimate G for the two crops. For both crops, 20-min R_n and G values for a given day were, in most cases, linearly related. On occasions, however, the relationship suffered from hysteresis problems, which tended to occur when the soil surface was wet as a result of rain or irrigation. For alfalfa, the relationship between R_n and G changed with changes in plant canopy height. Using multiple regression analysis an equation to estimate diurnal changes in G as a function of R_n and h was obtained. The model derived in this study to estimate G for alfalfa fitted measured G data much better than two other commonly used models (Allen et al., 1996; Clothier et al., 1986).

For tall fescue grass, the 20-min R_n and G averages for a given day were also well correlated, resulting in r^2 values greater than 0.90 for all days considered, except for days when the soil surface was wet. For tall fescue grass, plant canopy height did not significantly affect the relationship between R_n and G. These results, however, could have been due to the limited range of grass plant canopy heights included in this study. A simple linear equation to estimate G for tall fescue grass as a function of R_n was derived, which was found to fit measured data equally well as the model proposed by Allen et al. (1998), but that uses a single equation for both daytime and nighttime instead of two separate equations.

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